

Dielectric spectroscopy of chromium doped and undoped semi-insulating gallium arsenide

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Abstract : Charge transport mechanism in semi-insulating gallium arsenide is not yet fully established. We have performed Dielectric Spectroscopy of chromium doped and undoped semi insulating gallium arsenide. The transport mechanism in Cr doped semi insulating gallium arsenide is different from the undoped material. It has been observed that the undoped SI-GaAs shows a Low Frequency Dispersion (LFD) transport. In terms of the cluster model LFD transport is observed in charge carrier dominated systems in which the inter-cluster interaction provides some means of charge transport with its large accumulation within the bulk of the material. In Cr doped SI-GaAs a more uniform transport has been observed. Another observation of the study is the Schottky barrier processes on these wafers. It has been observed that the loss peaks are much broader than Debye loss peaks. The data have been analysed on the basis of *Universal* power law and use of the equivalent circuits have been made to interpret the data.

Keywords : Dielectric spectroscopy, semi-insulating gallium arsenide, chromium doped.

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1. Introduction

Gallium arsenide is considered to be semi-insulating if its resistivity is of the order of 10^7 to 10^9 ohm-cm. Semi-insulating gallium arsenide (SI-GaAs) has a great importance in the fabrication of integrated circuits. The preparation of the SI-GaAs is usually achieved by two methods. It is either grown by introducing controlled concentration of chromium or by creating an anti-site defect which is more commonly known as EL2 [1, 2]. The material prepared by either of the methods contain a large number of other defects but the models used to study the transport of the charge in this material are based on the ideal crystalline material [3]. Recent studies [4, 5] have shown that a fresh approach is required to look in the transport mechanism in SI-GaAs. In this paper we shall show that the charge transport mechanism in Cr doped and undoped SI-GaAs is quite distinct. The technique used is known as Dielectric Spectroscopy of Semiconductors (DSS) [5, 6].

2. Theory

The addition of chromium or the creation of anti-site defect i.e. EL2 along with other imperfections are characterized as deep levels within the band gap of the semiconductor.

circuits as shown in Figure 1. C_b is the capacitance of the Schottky barrier equal to $A\epsilon_b/w_b$, where w_b is the width of the space charge region and G_b is the dc-conductance of the barrier. C_v is the capacitance of the substrate equal to $A\epsilon_v/w_v$, where w_v is the thickness of the substrate and G_v is the dc-conductance of the substrate. Since the relaxation time, τ , of free charge carriers at the edge of a space charge region in a semiconductor falls in the nano second range, the dynamic response of this circuit is due to the interaction of C_b with the series resistance of substrate and is of Debye form. If the barrier is on a semi-insulating substrate, the relaxation time, τ_f , of free charge carriers in SI-GaAs with $\sigma_0 = 1 \mu \text{ Sm}^{-1}$ is of the order 100 microseconds which corresponds to a frequency range of KHz region and the loss peak frequency ω_s due to the interaction of barrier capacitance and series resistance of the volume would be much lower than τ_f

$$\omega_s = \frac{G_v}{C_b} = \frac{w_b \sigma_0}{w_v \epsilon_b} = \frac{w_b}{w_v \tau_f} \ll \frac{1}{\tau_f}.$$

The process of delayed emission of charge carriers from the deep levels where they cross the Fermi level in the space charge region to the conduction or valence band is characterized by

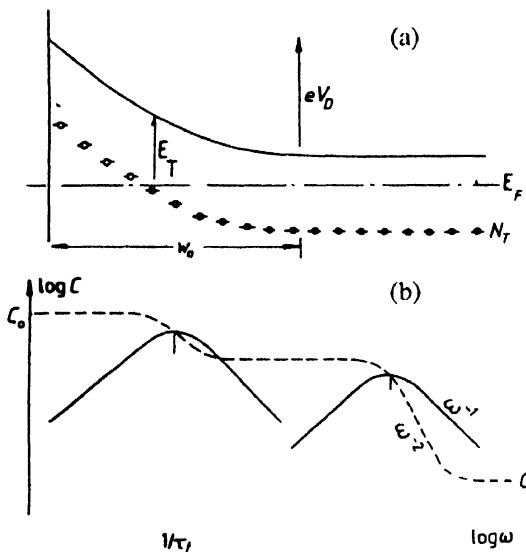


Figure 2. (a) The energy band diagram of an ideal Schottky barrier on an ideal semi-insulating substrate with a deep level at an energy level E_T below the Fermi level. (b) Frequency response the circuit shown in Figure 2(a)

another loss peak appropriate to emission rate and the magnitude of the dispersion in the real part of the capacitance would be proportional to the density of traps involved in the delayed emission process. The loss peak, $1/\tau_f$, corresponding to this process with the assumption that this is also of Debye form is shown in Figure 2. If the delayed emission process is non-Debye and follow a power law of the form [7] :

$$C'(\omega) - C_\infty \propto C''(\omega) \propto \omega^{n-1}$$

then the dielectric response of a Schottky barrier, provided its loss peak is symmetric can be represented by the Cole-Cole expression [9]. The dielectric response of this system can be represented by a series combination of an ideal capacitor and a *Universal* capacitor $C_n(\omega) = B (i\omega)^{n-1}$, where B is amplitude factor. The dielectric response of this circuit is shown in Figure 3. If this Schottky barrier is on a semi-insulating substrate which may not be ideal then the response of this system can be shown by placing Schottky barrier equivalent circuit in series with a parallel combination of a conductance and a *universal* capacitor

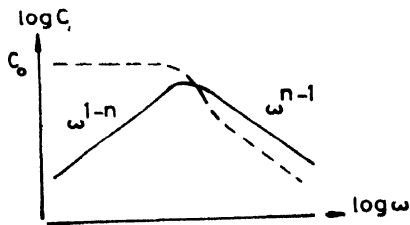


Figure 3. The frequency response of a Schottky barrier represented by a series combination of an ideal capacitor and a *universal* capacitor following a power law

representing the substrate with exponent $n_v < n$. In this case, the *universal* capacitor in the volume circuit represents a Low Frequency Dispersion (LFD) transport for which value of the exponent is very small [7, 10]. If the volume conductance dominates the LFD transport, then the dielectric response is due to the interaction of the dispersive capacitor representing the Schottky barrier in series with the volume resistance as shown in Figure 4. In this case, for $\omega > (BR)^{1/n}$, the dielectric loss slope is -1 and the capacitance slope is $-n-1$ while for

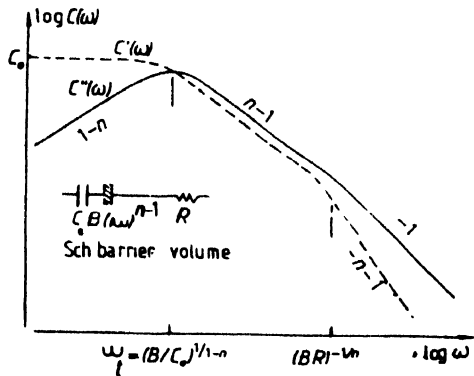


Figure 4. The frequency response of a Schottky barrier represented by a series combination of an ideal capacitor and a *universal* capacitor placed in series with resistance due to the substrate.

low frequency region $\omega < (BR)^{1/n}$ the response is solely due to the Schottky barrier and is determined by the Cole-Cole expression [9]. The dielectric loss peak is symmetric with a peak frequency equal to $(B/C_0)^{1/(1-n)} = 1/\tau_t$ where τ_t is the detrapping rate and C_0 is low

frequency limit of the barrier capacitance. The capacitance and dielectric loss, between ω_i and $(BR)^{1/n}$, are parallel with a Kramers-Kronig compatible ratio with slope equal to $(n - 1)$ [7]. However in the presence of a dc-conductance in the Schottky barrier, the low frequency side of the loss peak may not be visible.

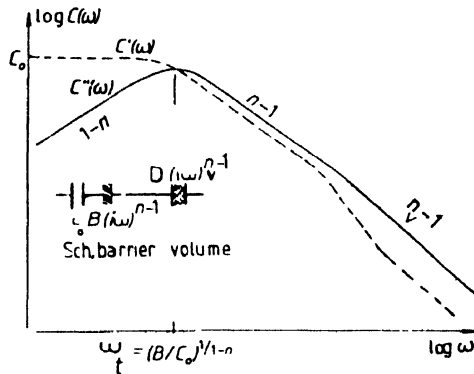


Figure 5. The frequency response of the same Schottky barrier in series with an LFD capacitor with exponent n_v , representing the volume of the substrate

If the volume response is dominated by the low frequency dispersion (LFD) transport in which n is very small [7, 10] then the dielectric response of this system is shown in Figure 5. In the low frequency region, the response is again Cole-Cole type but in the intermediate region, it is due to the interaction of the dispersive capacitor representing the Schottky barrier and the volume LFD capacitor. The real and imaginary parts of the capacitance are still diverging but with the dielectric loss component slope is equal to $n_v - 1$ and the real part slope would have values equal to $(B/D)^{1/n_v - n}$. At high frequencies, the dielectric response is due to volume LFD capacitor alone. The situation is clearly different from the series resistance case (Figure 4) in which the slope of dielectric loss component is strictly -1 and the slope $(n - 1)$ of capacitance is determined by the exponent of the dispersive capacitor representing the Schottky barrier. If the exponent of the volume LFD capacitor is close to zero, the distinction between the LFD and series resistance effect is difficult to make but the subtraction C''_0 from the real part of the capacitance at low temperature should give $K-K$ compatible slopes of the capacitance and dielectric loss in the high frequency region.

3. Experimental details

Both the wafers used in this study are of 500 micron thickness. The experiments were performed with suitable electrodes on opposite sides, placed in a vacuum cryostat with temperature control to $\pm 0.5K$ using a platinum resistance thermometer and Eurotherm temperature controller. The samples were mounted with the heat sinking compound on the copper base of the sample holder. Electrodes were applied in form of silver (Ag) paint but in one case ion bombardment implant was used to produce "ohmic" contacts.

Dielectric measurements were performed by using a fully automated SOLARTRON FREQUENCY RESPONSE ANALYZER (FRA). The details of the system are described elsewhere [11, 12]. This system provides a wider frequency range i.e. 10^{-4} to 10^4 Hz. with a dc-bias facility.

Data is recorded in the form of capacitance $C''(\omega)$ and dielectric loss $C'''(\omega)$ as a function of frequency with temperature as a parameter and is presented in the Log-Log form. The (\square) symbol represents capacitance while (+) symbol represents dielectric loss. The choice of the capacitance over susceptibility is due the uncertainty in the barrier thickness. The data sets are displaced one or two order of magnitude for the clarity. The normalization technique [13] has been used to compare the results of the samples and to derive the activation energies.

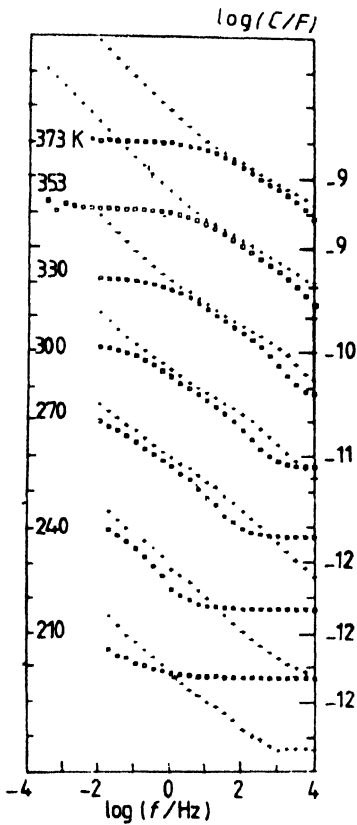


Figure 6. The dielectric response of undoped SI-GaAs sample in the temperature 270-373 K. The value of the rms signal is 0.1V.

4. Results and discussion

The dielectric response of an un-doped semi-insulating GaAs is shown in Figure 6 which has one contact implanted with 10^{15} cm^{-2} of phosphor ions of 170 KeV energy, with Ag paint over it and showed an "ohmic response". The other contact is Ag paint on the

untreated surface. The area of the contact is 20 mm^2 . The dielectric response is a function of temperature with zero bias at 0.1 V rms signal. The dielectric response may be understood in light of the circuit proposed in the theory section (Figure 5), in which a Schottky barrier is represented by a series combination of an ideal capacitor with a *Universal* capacitor placed in series with a dispersive capacitor representing a volume LFD transport process. At low temperature the behavior is dominated by volume LFD transport, shown clearly in the normalisation diagram, with a gradual development of a Schottky barrier process. Below 100 Hz at 300 K and above, there is a well defined parallelism between the capacitance $C'(\omega)$ and the dielectric loss $C''(\omega)$ with $n = 0.32$ suggesting that the barrier process is non-

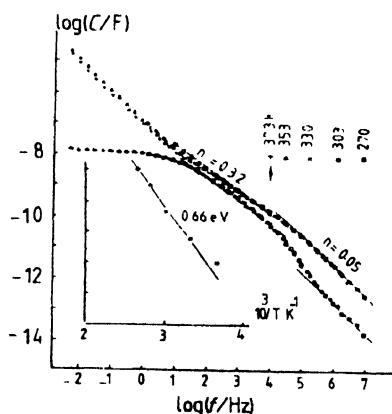


Figure 7. Normalization of the data shown in Figure 4 in the temperature range 270-373 K. Note the K-K compatible lines in the high frequency region with $n = 0.05$ for volume LFD process and K-K compatible lines with 0.32 represents the Schottky barrier region. Activation energy plot is also shown in the inset.

Debye. The normalisation of the data after subtraction of C_∞ together with the activation energy plot is shown in Figure 7. The activation energy in the temperature range 270-373 K is 0.66 eV. The exponent $n = 0.05$ corresponding to the volume LFD process, with K-K compatible positions, is shown in the diagram. The normalisation of the data shows that the exponent corresponding to the Schottky barrier process, $n = 0.32$, is independent of temperature. There is a slight scatter in the normalisation for the barrier conductance. The application of reverse bias between 0.5 to 5 volts showed a gradual decrease in the barrier conductance while the high frequency response did not reveal any effect.

In summary, the dielectric response of this sample can be divided into three categories; the volume response, the response due to the barrier-volume interaction and the barrier response. At low temperatures, the response is solely due to the volume process. Between 240-353 K, the response is due to the interaction of the Schottky barrier and the volume, while at 373 K the response is dominated by the Schottky barrier. None of these responses show the Debye-like behaviour and therefore have been described on the basis of the *Universal* power law [7]. The most important conclusion of this study is the volume LFD transport, shown clearly in the normalisation diagram (Figure 7) by K-K compatible

lines for the exponent $n = 0.05$ and is independent of either forward or reverse bias and of temperature.

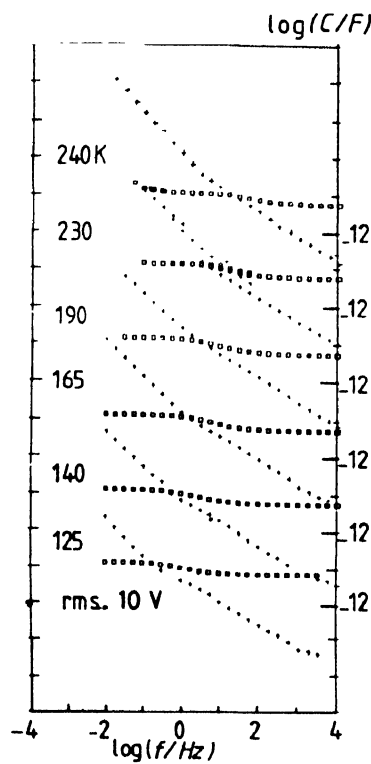


Figure 8. The low temperature (125-240) K dielectric response of Cr doped sample. The small dispersion in the capacitance is due to dipole-like hopping process within the volume of the material with a loss peak masked in dc-conductance

Figures 8 and 10 show the dielectric response of a chromium doped semi-insulating GaAs sample as a function of temperature with zero bias at 10 volt rms value. The Ag paint contacts are in the sandwich geometry and the area is 20 mm^2 . We have also attempted to record the data at lower rms values but due to the high scattering in the data this was discarded.

Figure 8 shows the dielectric response for the lower temperature range 125-240 K. The value of the C_∞ is compatible with the geometry of the sample. There is a slight dispersion in the capacitance $C'(\omega)$ which moves towards higher frequency side with increasing temperature. At high frequencies, the value of the dielectric loss exponent is 0.36, very distinct from the Debye behavior while at lower frequencies, the slope of the dielectric loss component is -1 suggesting that the domination of the dc-conductance. The normalisation of the data after subtraction of a suitable value of C_∞ from the data is shown

in Figure 9. The K-K compatible lines for $n = 0.36$ are also shown in the figure. This clearly suggests that the high frequency process follow the power law. The value of $n = 0.36$ for the loss process is different as compared to the near-Debye and as well as extended

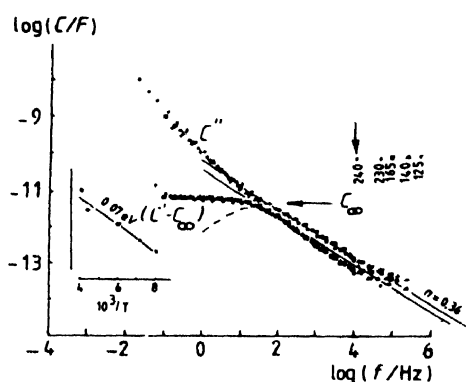


Figure 9. Normalization of the low temperature data shown in Figure 6 after subtraction of C_{∞} . The parallel lines in the high frequency region show the K-K compatibility with $n = 0.36$. The activation energy is also shown in the inset.

hopping processes [7]. Due to well defined saturation in the capacitance $C'(\omega)$ and -1 slope for the dielectric loss $C''(\omega)$, it cannot be considered as LFD transport. Since

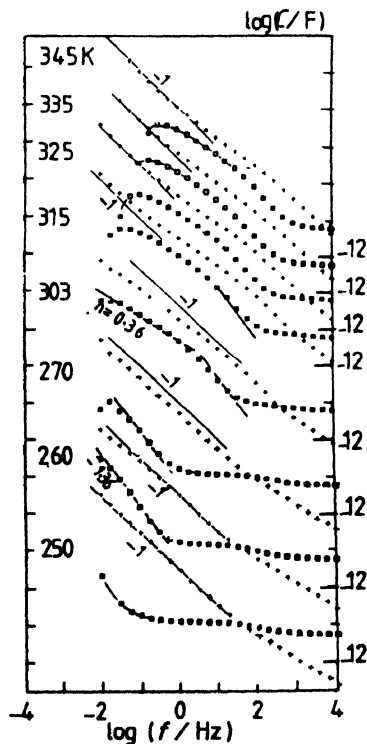


Figure 10. The high temperature dielectric response of the Cr doped sample.

activation energy is 0.07 eV, the possible interpretation of the data is that the process in question corresponds to hopping in the bulk between levels reasonable close to the Fermi level at an energy separation of ~ 0.1 eV. At higher frequencies, the reciprocating motions of the charge carrier gives a loss peak process while at lower frequencies, the onwads moment of the same carriers gives the dc-conduction. In Cr doped SI-GaAs this can happen among various chromium levels [15] or it could be due to the transitions between a chromium level and EL2 centre, since Cr^{2+} lie close to the Fermi level.

The most interesting feature of the high temperature data, shown in Figure 10, is the change in the spectral shape of the capacitance $C'(\omega)$ with increasing temperature. Below 300 K the slope of the capacitance $C'(\omega)$ is greater than -1 and slope of the dielectric loss $C''(\omega)$ is strictly -1 , indicating that the dielectric response is due to the interaction of a barrier with the series resistance of the volume as described in Figure 4. This is in contrast to the un-doped sample which gave a volume LFD transport. Around 300 K, the Schottky barrier process is fully developed with $n = 0.36$, while in the high frequency region the slope of the capacitance $C'(\omega)$ is -1.36 which is consistent with the series resistance effect. Another characteristic feature of these measurements is the onset of the negative capacitance at the lowest frequencies [5, 6]. The normalisation of the data between 300 and 345 K is shown in Figure 11. The activation energy is 0.55 eV. Because of the complicated response the data between 250 and 270 K cannot be normalize with the high temperature data.

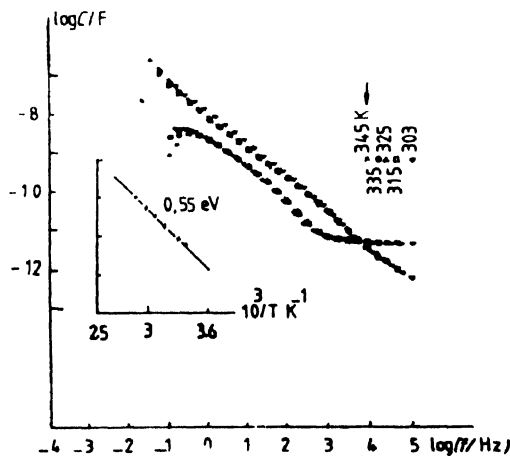


Figure 11. Normalisation of the data between 300-345 K of the Cr-doped presented in Figure 10.

5. Conclusions

The dielectric spectroscopy of the semi-insulating GaAs wafers have revealed that the volume response can be classified into two categories, namely the dipole-like behaviour and the volume LFD transport and in each case the exponent corresponding to the process is

independent of temperature or biasing. For Cr doped sample dipole-like response has been observed at low temperature. Below 240K the response clearly follows a power law with $n = 0.36$ and is in complete disagreement with the Debye-like loss mechanism. Not only is the exponent different from the Debye process but it also lies outside the range $0.6 < n < 1$ which is typically associated with the extended hopping processes [7, 10]. Well defined saturation of the capacitance $C'(\omega)$ and -1 slope for the dielectric loss $C''(\omega)$ in low frequency region rules out LFD transport. One possible explanation of this behaviour is the dipole-like hopping among several centres close to the Fermi level and the activation energy of 0.07 eV may be consistent with this process. At intermediate temperatures, the response of the Cr doped sample is due to the interaction of the series resistance of bulk and the Schottky barrier. This is clear from the slope of the capacitance $C'(\omega)$, which is greater than -1 whereas slope of the dielectric loss $C''(\omega)$ strictly -1 .

The other type of the volume response which has been observed in the undoped wafer is LFD transport. This response cannot be explained on the basis of a series resistance effect, because the slopes of capacitance $C'(\omega)$ and dielectric loss $C''(\omega)$ are less than -1 . The normalisation of the data after C_∞ subtraction has shown that the capacitance $C'(\omega)$ and the dielectric loss $C''(\omega)$ of the sample are in Kramers-Kronig compatible ratio with $n = 0.05$. This has clearly revealed that the undoped and Cr doped semi-insulating gallium arsenide have different volume responses.

In terms of the Dissado and Hill model [10, 15], the LFD transport is observed in charge carrier dominated systems in such cases the *inter-cluster* interaction provides some means of charge transport with its large accumulation within the bulk of the material. In material like semi-insulating GaAs, this phenomenon is new and it has recently been observed. This may be due the inhomogeneous distribution of impurities which may form domains as proposed by Pistoulet *et al* [4]. It is difficult to envisage how these domains can be related to the cluster model which is based on molecular excitations. In the absence of a theoretical model it is difficult to give any opinion about the true cause of the LFD transport in undoped SI-gallium arsenide or for a uniform transport in Cr doped sample.

The other important observation of this study is the dielectric response of the Schottky barrier on the semi-insulating substrate. The exponent $n = 0.32$ for the undoped sample and 0.36 for the Cr doped sample corresponding to the barrier dispersion, clearly shows that deep level emission process does not follow an exponential time dependence which in the frequency domain should have Debye like response. Although we are not sure that the loss peak due the Schottky barrier process is symmetric or not, the well defined saturation of capacitance $C'(\omega)$ cannot be explained by a *Universal* capacitor alone. The use of an ideal capacitor in series with a *Universal* capacitor for a Schottky barrier appears to be reasonable choice because no circuit combination other than this can explain a non-Debye loss peak with well defined saturation in the capacitance. Another feature to note is the appearance of dc-conductance in the low frequency region near the loss peak frequency. This

shows that the magnitude of the volume and barrier conductance are comparable within an order of magnitude. Examination of the data for both the samples at 300 K shows that the barrier conduction is approximately 4 times less than the volume conductance. This suggests that Schottky barrier on SI-GaAs is leaky. One more feature of this study is the same value of power law exponent, $n = 0.36$ for the Schottky barrier and for the volume process in the Cr-doped SI-doped SI-GaAs. This value is close to the exponent ($n = 0.32$) for the barrier process in the undoped SI-GaAs. Although the dipole-like process in the bulk of a sample and the Schottky barrier are different but the similarity in their exponents is surprising and it requires more experimentation.

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